CHARACTERISATION AND EFFICIENCY TEST OF A LI-ION ENERGY STORAGE SYSTEM FOR PV SYSTEMS

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ABSTRACT: Li-ion batteries are modern electrical energy storage systems which are undergoing an intense development in their technological features. Their high specific energy, efficiency and durability, together with the lowering of their production costs, are placing them as one of the most promising actors in the field of electrical energy storage technology used as tool for integrating renewable energy sources. But due to the fact that they are in an early stage of development, their reliability must be trusted. This paper describes a method and the results for testing round trip efficiencies of a modern Li-ion battery based energy storage system integrated in a PV system. According to the related standards, the efficiency of a battery and an inverter/charger has been characterised, under technical restrictions and specific operation conditions for its use with PV systems.
Keywords: Batteries, Characterisation, Energy Performance, Electrical Properties, Storage.

1 INTRODUCTION

Storing energy is becoming more important in order to integrate fluctuating renewable energy sources in the grid. Modern Electrical Energy Storage (EES) systems are effective tools for decoupling the production of clean energy from its consumption, both in utility size and distributed generation units. Since some decades, classic lead acid batteries have been used for storing energy especially in rural or autonomous photovoltaic applications [1]. But in the last years, the high penetration of renewables in the grid has drawn up a new scenario for storage systems. Batteries are being considered as effective tools in balancing production and consumption of clean energy, so lead acid batteries have been installed also in distributed generation systems. In countries like Germany, government policies were applied to support the installation of storage systems in private households, in order to encourage the local consumption of generated PV power [2]. In this context, they can be used for shifting generated power from central hours of a day, where there is plenty of solar resource but little local consumption to evening hours with few resource and lots of consumption. Mature technology, low cost and the ability to supply high currents are the attractive features of lead acid batteries [3]. However, classic batteries have some limitations and it is necessary to develop new storage systems.

Li-ion batteries are modern energy storage systems which are undergoing an intense development in their technological features, especially in the composition of their electrochemistry [4]. Their high specific energy, efficiency and durability, are placing them as one of the most promising actors in the field of EES technology. The highly reactive nature of the lithium is the main reason of those good electrochemical properties [3][5]. The lowering of their production costs will allow a wide application of these systems and several studies identify technological key points which will help on this matter [6][7]. Moreover, rising retail prices and falling FiT will make these systems financially more attractive [2]. The massive integration of such systems will allow high penetration of fluctuating renewable energy sources (RES) such as PV in electricity grids, reducing their impact. But due to the fact that they are in an early stage of development, their reliability must be trusted. The purpose of this work is to characterise a commercial Li-ion battery in real operation, used for storing and managing photovoltaic energy in distributed generation systems. The paper describes a method and the results for testing round trip efficiencies of a modern Li-ion battery based EES system which is used by IES-UPM for developing modern energy management strategies for PV systems. For these studies, an energy management laboratory has been created. The laboratory is formed by the battery, which is operated by a bidirectional inverter/charger, a grid connected PV generator, electrical loads in a real Smart Home and a complete I&C equipment, which registers all electrical parameters and commands PV and battery inverters.

2 ENERGY STORAGE SYSTEM SPECIFICATIONS

For renewable energy storage applications, it is necessary to develop specific Li-ion battery systems. In this case, the selected option is a Cegasa EES solution, which consists of a stationary NMC type lithium string operated by a Battery Management System (BMS) module and connected to the local grid by an Ingeteam inverter/charger. This type of battery is formed by two energy modules connected in series. Each module contains 36 cells in series, divided in 6 strings of 6 cells each one. Thanks to the modular architecture, with this solution the required capacity of the EES is achieved adding extra modules.

2.1 Li-ion battery specifications

The following table describes the electrical specifications of the storage system [8]. This system is sized according to the energy management laboratory, taking into account that the operation mode is domestic.

Table I: Li-ion battery specifications (DC bus of EES)

Electric parameter	Value
Nominal voltage	266.4 V
Maximum voltage (SOC 100%)	302.4 V
Minimum voltage (SOC 0%)	194.4 V
Nominal discharge current 1C	40 A
Maximum discharge current	50 A
Maximum charge current	50 A
Maximum constant power	6.4 kW
Peak power (2 min)	6.9 kW
Peak power (3 sec)	7.9 kW

Nominal capacity	10.6 kWh

2.2 EES efficiency

In order to characterise the full EES, it is necessary to test the efficiency taking into account its two subsystems. The overall efficiency of the EES is calculated as the combination of both battery and inverter/charger efficiencies, during the complete process of charging and discharging the stored PV energy.

On the one hand, the manufacturer does not specify an efficiency of this particular battery but in the specific literature there are different values for this parameter. For example, in reference [9] it is explained that operating a $LiFePO_4$ battery between SOC limits of 30-70%, the calculated efficiency is 95%. But given that our test will be according to other limits and the battery type is NMC, it is necessary to test its efficiency.

On the other hand, the efficiency of the inverter/charger must also be taken into account. This type of power electronics device has been widely tested and, for example, in reference [9] it is said that their efficiency is usually around 97-98% working at nominal power. However, in order to characterise the EES of our laboratory, it is necessary to analyse the behaviour of this device working together with this specific Li-ion battery.

2.3 Real capacity and technical restrictions

Although the nominal capacity of the battery, as shown in Table I, is 10.6 kWh, the manufacturer does not recommend using all of that capacity. Each cell has a maximum and a minimum recommended voltage and surpassing or going below these limits can involve damage of their electrochemical properties. Moreover, beyond these limits the battery turns very inefficient and charging beyond a maximum SOC or discharging below a minimum SOC will result in a low useful energy exchange compared to the generated losses.

As a consequence, in order to characterise the battery it is necessary to limit the nominal capacity to a real one, E_{real} (kWh). Following manufacturer's recommendations EES is operated considering $V_{cell,min}$ = 3.3V and $V_{cell,max}$ = 4.05V as set values for stopping discharge/charge processes. As a consequence, the test will characterise E_{real} under recommended conditions, obtaining the values of SOC_{min} and SOC_{max}.

However, due to auxiliary energy consumption of internal devices, when the battery is unused during long periods, it can be autodischarged. If this occurs when SOC is in the minimum range, it can be dangerous for the cells. In order to avoid this problem, a maximum Depth of Discharge (DOD) has been considered as a security limit. In the literature, this limit is usually 80%, so discharge is limited to $SOC_{min,DOD}$=20%.

2.4 Operation of the EES in an efficiency test

In every application of the energy storage system, the inverter/charger is the responsible for the operation of the battery. The BMS controls the energy flow over the different energy modules and cells and monitors all electrical parameters in order to assure that the current, cell voltages and temperatures are between specified values. This system communicates via CANopen protocol with the inverter/charger, so the last one can have the restrictions and proceed with the appropriate discharge/charge process.

As explained in the previous section, the ESS operates with cell voltages limited to $V_{cell,min}$ and $V_{cell,max}$. So a full discharge/charge cycle of the EES, starting from a fully charged battery (limited SOC_{max}) is the following sequence:

1) Inverter starts discharge process, with user defined power, limited to inverter AC nominal power, $P_{inv,n}$. It corresponds to a battery DC power, P_{bat} limited to specifications (Table I).
2) Battery cells voltage decrease as battery discharges. Due to the dispersion of cells, when the first one achieves $V_{cell,min}$ the inverter stops the process. At this moment SOC_{min} is reached.
3) Inverter enters in battery charger mode, with user defined AC power limited to $P_{inv,n}$. It corresponds to battery DC power limited to specifications. This process is performed in constant current and increases battery voltage.
4) When the first cell achieves $V_{cell,max}$, the charger captures the battery voltage V_{batt} and decreases the charging current in order to keep constant the voltage. When the current reaches a minimum preset value, the process stops and the SOC_{max} is achieved.

3 METHODOLOGY OF EFFICIENCY TESTS

3.1 Applicable standard: IEC 61427-2

The proposed tests are performed under IEC 61427-2 standard, which rules the conditions and procedures for testing a battery used for renewable energy storage in different conditions. This standard relates to batteries used in EES applications and the associated methods of test, which are proposed for the verification of endurance, performance and their reaction to specified or anomalous occurrences during operation [10]. This standard, part 2 of the 61427 series, deals with batteries used in grid-connected applications and is essentially battery chemistry neutral (agnostic). Related power conversion and interface equipment is not covered by this standard. Due to our usage pattern, the applicable chapter is the one which rules the tests for time-shift service conditions.

3.2 Energy Management Laboratory

The Solar Energy Institute of the Polytechnic University of Madrid has created a laboratory in order to develop and test advanced energy management strategies for grid-connected PV+EES systems. The laboratory is composed of a PV generator, Li-ion battery EES system, controllable loads in a Smart Home and a powerful I&C equipment. Each power device is described in Table II. PV generator, EES and the loads are connected to the local grid, so the connection of all three systems is in the 230V AC line.

Table II: Energy management laboratory equipment

Device	Description	P_n
PV array	9 x Isofoton ISF-240/20	2.25 kW
PV inverter	Ingeteam Ingecon Sunlite	5 kW
Battery inv/ch	Ingeteam EMS Home	5 kW

Figure 1: Energy management laboratory, with the battery, inverter/charger, PV inverter and I&C equipment.

Figure 2: PV string installed on Smart Home façade (9 x-Si modules, 2.25kWp). The controllable loads include lighting, home appliances and cooling system.

3.3 Instrumentation & Control equipment specifications

Due to the conditions stated in the standard, the instrumentation equipment used for this experiment must follow certain resolution and quality specifications. In order to guarantee correct measurement of all parameters involved in the test, high resolution digital power instruments have been used. The test is performed using grid power, so for the purpose of the efficiency test it is not necessary to register the parameters of PV generator and local loads. Relevant registered parameters are transmitted real time vía RS-485 to a TCP/RS converter and by means of Ethernet communication a LabVIEW application collects all them.

The controller that rules the system and collects the data is a NI-PXIe industrial controller, where a LabVIEW application performs the test according to the procedure explained in IEC 61427-2.

Table III: Efficiency test I&C equipment specifications.

Instrument	Model
AC Wattmeter for EES	Circutor CVM-D
DC indicator, unidirectional (2)	Circutor DH96-CPM
TCP/RS converter	Circutor TCP2RS+
Industrial controller & LabView	NI-PXIe

3.4 Test procedure

For this study, two different tests have been performed. First of all, in order to characterise the battery following the IEC standard, the test conditions explained in it have been fulfilled. But in order to characterise the full potential of the EES, another test has been carried out using the nominal power of the inverter/charger. On the following, both procedures are explained

- Test according to IEC61427-2

According to IEC 61427-2, the battery is fully discharged and immediately charged, using the full real capacity of the battery along a day. Following the specifications of the manufacturer and the IEC standard, the appropriate discharge/charge power rate is configured. Monitoring the energy flow along the whole process and registering battery voltage and current by means of advanced I&C equipment, round trip efficiencies for different discharge/charge rates can be calculated and V_{bat} and I_{bat} curves can be drawn. The parameters to monitor are listed below:

Table IV: EES parameters to monitor during the test.

Parameter to monitor	Variable name
Total discharged energy (DC)	E_{dis} (kWh)
Total charged energy (DC)	E_{char} (kWh)
Battery discharge/charge power (DC)	P_{bat} (kW)
Inverter/charger power (AC)	P_{inv} (kW)
Battery voltage (DC)	V_{bat} (V)
Battery current (DC)	I_{bat} (A)

After reaching full charge as an initial state, the test starts with the following discharge/charge sequence, carried out in an uninterrupted way:

1) Discharge for 480 minutes with constant DC power $P_{bat.d}$ until V_{bat} reaches lower limit set by $V_{cell,min}$. In order to perform a full discharge during 8 hours, the constant power must be configured following Eq. 1, explained in [10]:

$$P_{bat,d} = \frac{x \cdot 3}{n} = 1\,kW \quad x = 1 \;\; ; \;\; n = 3 \tag{1}$$

2) Charge for around 480 minutes with constant DC $P_{bat,c}$. After that time, the battery reaches again to a SOC of 100%. Owing to the losses, if the charge is performed at the same power rate as discharge, the needed time for achieving initial SOC will be higher than discharge time.

3) The efficiency η_{bat} in time-shifting service is defined as the ratio between net energy discharged and total energy charged. This ratio takes into account the auxiliary energy consumption of the BMS, necessary for the right operation of the battery.

$$\eta_{bat} = \frac{E_{dis}}{E_{char}} \tag{2}$$

Figure 3 explains the full process with a 16 hours duty cycle. 100% of the SOC is considered the real capacity of the battery, under safety limits recommended by the manufacturer.

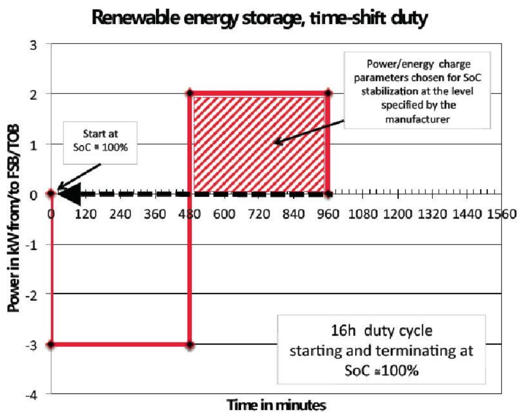

Figure 3: Full discharge-charge cycle of a test is performed during 16 hours, according to IEC-61427-2 Source: [10].

- Test at inverter nominal power

The process for testing the response of the EES at full capacity follows the same procedure as stated before, but exchanging energy with the battery at nominal inverter/charger power. Consequently, the duration of the test will be shorter and the efficiency will vary from previous conditions. For an accurate test, the charge and discharge power in the DC bus must be the same so we will set it up at 4.6 kW, due to the fact that the inverter AC nominal power is limited to 5 kW. So in AC bus, charge power and discharge one will be different because of the inverter efficiency and the energy flow directions. As a matter of convenience, the sign of discharge power is considered positive and charge power negative. Test parameters will be the following:

$$P_{bat,d} = 4.6\,kW \rightarrow P_{inv,AC,d} = 4.48\,kW$$
$$P_{bat,c} = -4.6\,kW \rightarrow P_{inv,AC,c} = -5\,kW \quad (3)$$

4 RESULTS

After several tests under IEC 61427-2 conditions and inverter nominal power conditions, the round trip efficiency of the battery has been calculated. These results check the specifications provided by the manufacturer and they are useful for giving feedback of real performance in different commercial operation modes of the system.

4.1 Battery characterisation at IEC61427-2 conditions

The first test is a full discharge/charge cycle test at $P_{bat,d}$=1kW DC power set point. The inverter measures V_{bat} and calculates the required current for discharging $P_{bat,d}$ power from battery and supplying AC power to the grid at the set $P_{inv,d}$. That current is kept constant for short periods in steps, because the inverter does not make that calculation real time. That means that the power is not exactly constant all the time and it varies in a small range of 16W (1.6%) during discharge and 12W (1.2%) during charge. However, as V_{bat} decreases considerably, the inverter updates the current setting it upper, in order to keep constant in average the power supplied by the battery.

- Discharge at IEC61427-2 conditions

In Figure 4 it can be seen that the battery discharges at constant power over the period, reducing its voltage while the inverter increases demanding current in order to keep constant the power along the time. The discharge process is ended when the most discharged cell voltage achieves $V_{cell,min}$ = 3.3 V, which means a V_{bat}=240.9 V. Monitored values are shown in Table V.

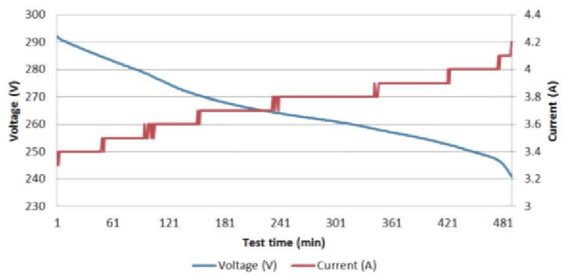

Figure 4: Discharge cycle of aprox. 480 minutes at $P_{bat,d}$= 1kW, according to IEC-61427-2.

Table V: Test results at $P_{bat,d}$=1 kW discharge.

Parameter to monitor	Value
$V_{bat,start}$	291.9 V
$V_{bat,stop}$	240.9 V
$I_{bat,start}$	3.4 A
$I_{bat,stop}$	4.2 A
$P_{bat,d}$ range (aprox. 1 kW)	0.99-1.015 kW
E_{dis}	8.75 kWh
η_{inv}	93.15%

According to manufacturer's electrochemical tests, this stop value of voltage corresponds to a SOC_{min} of 5%.

- Charge at IEC61427-2 conditions

In Figure 5 it can be seen that the battery is charged at constant power over the period, increasing its voltage while the inverter decreases demanding current in order to keep constant the power along the time.

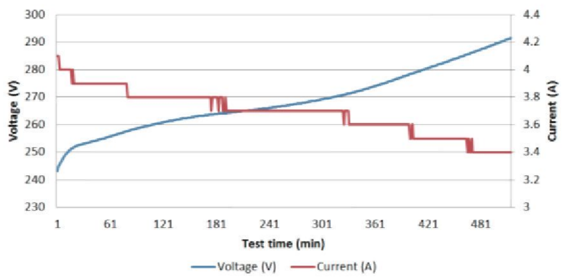

Figure 5: Discharge cycle at $P_{bat,c}$= -1kW, according to IEC-61427-2. The duration is longer, as the energy flow is higher than in discharge process.

Table VI: Test results at $P_{bat,c}$ = -1 kW charge.

Parameter to monitor	Value
$V_{bat,start}$	241.1 V
$V_{bat,stop}$	291.5 V
$I_{bat,start}$	-4.1 A

$I_{bat,stop}$	-3.4 A
$P_{bat,c}$ range (aprox. -1 kW)	-1.009, -0.997 kW
E_{char}	9.19 kWh
η_{inv}	93.13%

According to manufacturer's electrochemical tests, this stop value of voltage corresponds to a SOC_{max} of 90%.

- Round trip efficiency at IEC61427-2 conditions

Efficiency is calculated taking into account all energy flows supplied from and into the battery. In charging process, the DC power supplied by the charger and monitored by the DC indicator is used for charging the battery, but after some losses the effective energy is lower. Both in charge and discharge processes, some energy is lost as heat and another part consumed as auxiliary energy by the BMS unit. In discharge process, the battery supplies effective DC power monitored by DC indicator. This value is the available energy after battery losses, so in order to find the efficiency of the battery, the effective discharge energy must be compared with the total charging DC energy, using the following equation.

$$\eta_{bat,IEC} = \frac{E_{dis}}{E_{char}} = \frac{8.751}{9.194} = 0.9518 \rightarrow 95.18\% \quad (4)$$

4.2 Battery characterisation at inverter nominal power

This test is a full cycle test at 4.6 kW DC power set point. The inverter acts as in the previous mode, but given the higher power supplied and absorbed by the battery, V_{bat} decreases and increases faster in the discharge and charge processes.

- Discharge at inverter nominal power

Figure 6 shows the constant power discharge, reducing the voltage faster than in IEC standard test. The discharge process is ended when the most discharged cell voltage achieves Vcell,min = 3.3 V, which means a V_{batt}=240.4 V.

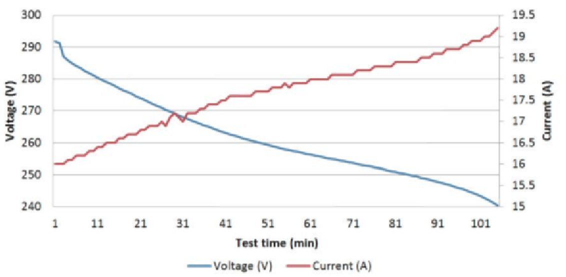

Figure 6: Discharge cycle of aprox. 105 minutes at $P_{bat,d}$= 4.6kW, close to inverter nominal power.

Table VII: Test results at $P_{bat,d}$=4.6 kW discharge.

Parameter to monitor	Value
$V_{bat,start}$	291.8 V
$V_{bat,stop}$	240.4 V
$I_{bat,start}$	15.8 A
$I_{bat,stop}$	19.2 A
$P_{bat,d}$ range (aprox. 4.6 kW)	4.59-4.63 kW
E_{dis}	8.793 kWh
η_{inv}	94.38%

According to manufacturer's electrochemical tests, the stop value of voltage corresponds to a SOC_{min} of 5%.

- Charge at inverter nominal power

Figure 7 shows the constant power charge, increasing the voltage faster than in IEC standard test. The charge process is ended when the most charged cell voltage achieves $V_{cell,max}$ = 4.05 V, which means a V_{batt}=291.8 V.

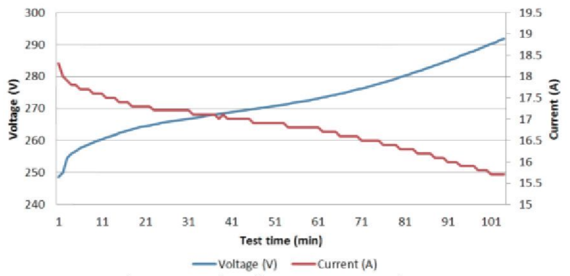

Figure 7: Charge cycle of aprox. 105 minutes at P_{char} = -4.6kW, close to inverter nominal power operation mode.

Table VIII: Test results at P_{dis}=-4.6 kW charge.

Parameter to monitor	Value
$V_{batt,start}$	248.6 V
$V_{batt,stop}$	291.8 V
$I_{batt,start}$	-18.3 A
$I_{batt,stop}$	-15.7 A
P_{char} range (aprox. 4.6 kW)	-4.6 , -4.58 kW
E_{char}	9.227 kWh
η_{inv}	94.36%

According to manufacturer's electrochemical tests, the stop value of voltage corresponds to a SOC_{max} of 90%.

- Round trip efficiency at inverter nominal power

Efficiency is calculated the same way as in IEC standard tests. In order to find the efficiency of the battery, the effective discharge energy must be compared with the total charging DC energy, using the following equation.

$$\eta_{batt,nom} = \frac{E_{dis}}{E_{char}} = \frac{8.793}{9.227} = 0.9529 \rightarrow 95.29\% \quad (5)$$

4.3 Inverter efficiency

For an accurate characterization of the whole ESS, it is necessary to test the inverter/charger in both operation modes. In order to check this, it is necessary to use the monitored $P_{inv,AC}$ and $P_{bat,d}/P_{bat,c}$ instant values. The efficiency of the inverter/charger is the relation of its AC and DC bus powers.

Inverter efficiency in each process is calculated obtaining the whole process mean value of instant efficiencies. Instant efficiencies are the relation of the values measured by the meters:

$$\eta_{inv,d,t} = \frac{P_{inv,t}}{P_{bat,d,t}} \quad ; \quad \eta_{inv,c,t} = \frac{P_{bat,c,t}}{P_{inv,t}}$$

$$\eta_{inv,d} = \bar{\eta}_{inv,d,t}$$
$$\eta_{inv,c} = \bar{\eta}_{inv,c,t} \tag{6}$$

According to each test, the inverter efficiency is the following

IEC 61427-2 : $\eta_{inv,d} = 93.15\%$
$\eta_{inv,c} = 93.13\%$

Inverter $P_{inv,n}$: $\eta_{inv,d} = 94.38\%$
$\eta_{inv,c} = 94.36\%$

5 Electrical Energy Storage system characterisation

Finally, using the results obtained in previous tests we can model the Li-ion battery based EES using an efficiency that gives the effective energy that can supply the EES in AC bus compared to the PV energy previously stored in it. For this, charge and discharge efficiency of the inverter and the battery efficiency must be taken into account as following:

$$\eta_{EES} = \frac{E_{dis} \cdot \eta_{inv,d}}{E_{char}/\eta_{inv,c}} = \frac{E_{dis}}{E_{char}} \cdot \eta_{inv,c} \cdot \eta_{inv,d} =$$
$$= \eta_{bat} \cdot \eta_{inv,c} \cdot \eta_{inv,d} \tag{7}$$

Moreover, the effective capacity of the battery can be obtained applying the SOC_{min} and SOC_{max} technical restrictions to the manufacturer's nominal capacity. Also, taking into account further restrictions in order to avoid high DOD values, an additional $SOC_{min,DOD}$ restriction has been proposed.

Following equations give a final value for each of the testing conditions:

IEC 61427-2:

$$\eta_{EES,IEC} = \eta_{bat,IEC} \cdot \eta_{inv,c,IEC} \cdot \eta_{inv,d,IEC} =$$
$$= 0.9518 \cdot 0.9313 \cdot 0.9315 = 0.8257$$

$$\eta_{EES,IEC} = 82.57\% \tag{8}$$

Inverter nominal power:

$$\eta_{EES,nom} = \eta_{bat,nom} \cdot \eta_{inv,c,nom} \cdot \eta_{inv,d,nom} =$$
$$= 0.9529 \cdot 0.9438 \cdot 0.9436 = 0.8486$$

$$\eta_{EES,nom} = 84.86\% \tag{9}$$

EES effective capacity:

$$SOC_{min} = 5\% \;;\; SOC_{max} = 90\%$$

$$E_{bat,real} = (SOC_{max} - SOC_{min}) \cdot E_{bat,nom} =$$

$$= 0.85 \cdot 10.6 = 9.01\, kWh \tag{10}$$

EES effective capacity (DOD=80% security restriction):

$$SOC_{min,DOD} = 20\% \;;\; SOC_{max} = 90\%$$

$$E_{bat,real,DOD} = \left(SOC_{max} - SOC_{min,DOD}\right) \cdot E_{bat,nom=}$$

$$= 0.70 \cdot 10.6 = 7.42\, kWh \tag{11}$$

5 CONCLUSIONS

This paper has analysed the characterisation method needed to model a Li-ion based EES system. The tests carried out for this purpose have been developed according to IEC 61427-2 standard and in nominal power conditions of the inverter. The battery efficiencies obtained in the tests are quite similar in both tests, being 95,18% and 95.29% respectively. However inverter efficiencies are around 93.15% in the first case while at nominal power it increases until around 94.38%. This occurs because when the inverter operates in power rates well below the nominal conditions, its efficiency drops slightly. That results in EES round trip efficiencies of 82.57% and 84.86%, depending on the test power.

Moreover, the technical and DOD safe operating limits of the EES charge and discharge processes have been set up, correcting the nominal capacity of such a system and characterising its effective storage capacity. The nominal capacity of 10.6 kWh, drops to 9.01 kWh applying manufacturer's technical conditions and to 7.42 kWh keeping a DOD above 20%. That means that an 85% or 70% of the nominal capacity is effective, depending on the security limits.

These features are necessary for modelling grid connected PV+EES systems, in order to dimension, design or simulate such systems in an accurate way. By using the real efficiencies of the whole EES under different operation conditions and knowing the effective capacity, it is possible to model the energetic behaviour of Li-ion modern battery based storage systems.

6 ACKNOWLEDGMENTS

This work has been cofinanced by the European Commission in the frame of Seventh Framework Programme, in the context of PVCROPS project (PhotoVoltaic Cost r€duction, Reliability, Operational performance, Prediction and Simulation), contract No. 308468.

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